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Perceptual completion in a dynamic scene: An investigation with an ambiguous motion paradigm

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Abstract

In this study we employed the streaming–bouncing stimulus to investigate aspects of dynamic occlusion, e.g., of objects that temporarily move under occlusion while covertly being tracked. Two occluders, both either luminance-defined or invisible (virtual), were placed on the trajectories of the moving objects in the streaming–bouncing stimulus. We found that the bouncing percept was dominant when the objects moved under luminance-defined occluders but not when they moved under virtual occluders. Perceived motion direction thus varied with occluder visibility. The results seem to suggest that perceptual completion of a moving object interferes with constant motion processing of the same object.

Keywords: Occlusion; Perceptual completion; Motion; Streaming–bouncing

1. Introduction

Perceptual completion in a dynamic scene differs from completion in a static scene in that (a) it concerns objects that move under occlusion, while (b) the objects are being tracked by the visual system (e.g., Behrmann, Zemel, & Mozer, 1998; Watamaniuk & McKee, 1995; Yantis, 1992, 1995), as in tasks related to locomotion such as driving in traffic. Tracking can occur by (covertly) engaging attention to a moving object that moves under a visible, luminance-defined occluder or gradually disappears and reappears from behind an occluder that is less clearly visible or not visible at all, for example in the dark. Neurophysiological data regarding perceptual completion in a dynamic scene come from a study by Assad and Maunsell (1995), who showed that cells in the posterior parietal cortex can signal the presence of motion of an occluded object in the absence of retinal stimulation. Scholl and Pylyshyn (1999) suggested that the cells identified by Assad and Maunsell (1995) could be useful parts of an attentive tracking system mediated through activity in the posterior parietal cortex (see also Culham et al., 1998). Still few behavioral data, however, are available on constant motion processing and perceptual completion of (covertly) tracked objects that move under occlusion.

In this study, we explored whether processes of perceptual completion of occluded objects interfere with constant motion processing of the same objects. In order to do so, we used a stimulus in which two occluders were placed in a so-called 'streaming–bouncing' stimulus (Metzger, 1934; Michotte, 1946/1963). A typical streaming–bouncing stimulus consists of two identical visual objects that move laterally towards each other, overlap and then move away from each other. We can see the two objects either as moving through each other (streaming) or as reversing their motion trajectory at their meeting point (bouncing). The stimulus is ambiguous, but not completely bistable; the streaming percept is the dominant percept in more than 80% of the trials in a normal viewing situation (Shimojo et al., 2001).

Although the perceptual mechanism that underlies the perception of the streaming–bouncing stimulus is not yet

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completely understood, it is argued that attention can modulate its perception. A number of studies have shown that 'bouncing' can become the dominant percept when a transient stimulus (a brief sound or a flash) is presented at or near the meeting point of the moving objects (Sekuler, Sekuler, & Lau, 1997; Shimojo et al., 2001; Watanabe & Shimojo, 2001). It is argued that presenting such a transient may influence motion processing of the moving objects through attention distraction (Shimojo et al., 2001; Watanabe & Shimojo, 1998). Watanabe and colleagues argued that attention is required for constant motion processing that leads to the perception of streaming. This idea is supported by studies that used different stimuli to show that attention is required to successfully track multiple objects (e.g., Scholl & Pylyshyn, 1999). When a transient stimulus is presented in the streaming–bouncing stimulus, however, attention is drawn away from constant motion processing and allocated instead to the interpretation of the transient. As a consequence, bouncing becomes the dominant percept. Watanabe and Shimojo (1998) supported the idea about the involvement of attention in transient-induced bouncing by showing that endogenous attention distraction, in a dual-task method, also resulted in dominant bouncing.

Because of the motion-direction ambiguity in the streaming–bouncing stimulus and the likelihood that attention allocation can modulate its perception, we added two occluders to the streaming–bouncing stimulus to investigate the effect of occlusion on constant motion processing of attentively tracked, moving objects. The two occluders were placed on the motion trajectories of the two moving objects in the streaming–bouncing stimulus in such a way that the meeting point of the moving objects was not occluded (Fig. 1). By contrast, Sekuler and Sekuler (1999), in an earlier study, used just a single occluder that was placed over the meeting point of the moving objects. Whereas they found dominant streaming in their paradigm, informal observations (Remijn & Ito, 2004) have shown that with two occluders flanking the moving objects' meeting point, occluder-induced bouncing could become the dominant percept. The same informal observations showed that dominant bouncing disappeared in non-occlusion conditions in which the moving objects moved in front of two fixed objects. One reason why Sekuler and Sekuler (1999) did not obtain occluder-induced bouncing may be that by occluding the moving objects' meeting point, the ambiguity was taken out of the streaming–bouncing stimulus. Without visible object impact, the visual system would have no reason to perceptually complete a reversal in the objects' trajectories, if it could.

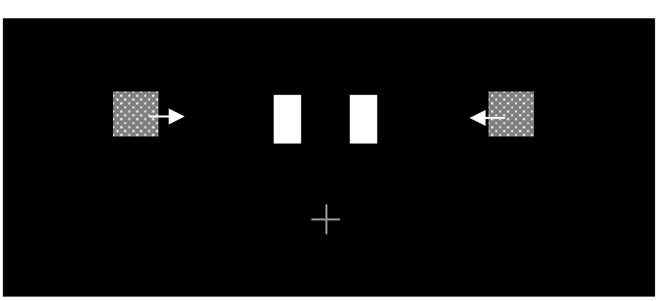

Fig. 1. The basic streaming–bouncing stimulus used in this study. The stimulus consisted of two identical squares that moved towards each other, overlapped and then moved away from each other. Two occluders were placed on the trajectories of the moving objects in such a way that the meeting point of the moving objects was not occluded.

In this study, we will report three experiments that show that under certain conditions of size and spatial separation between the occluders, occluder-induced bouncing occurs with luminance-defined occluders, but not with occluders that have the same luminance as the background ('virtual' occluders). The perceived motion direction of the moving objects thus changes with type of occlusion, although the retinal image of the objects' motion remains the same. Although we must be aware that the results we describe here might be particular to the streaming–bouncing stimulus only, they may suggest that processes of occlusion and perceptual completion in a dynamic scene interfere with constant motion processing of an object that moves under occlusion while (covertly) being tracked. We will discuss two tentative explanations for the results.

2. Experiment 1

In this experiment, we explored whether occlusion events affect the perceived motion direction of the two moving objects in a streaming–bouncing stimulus.

We varied the spatial separation between the occluders that were placed on the moving objects' trajectories, as well as the contrast between the occluders and the background. We varied the spatial separation between the occluders to test whether the spatio-temporal proximity between the start of the occlusion of the moving objects and the meeting point of the moving objects influenced the perception of the streaming–bouncing stimulus. An occlusion event can be regarded as a transient event (Sekuler & Sekuler, 1999), in that it alters retinal image, and it is known that external transients (a brief sound or a flash) induce bouncing when they appear in close spatio-temporal proximity to the moving objects' meeting point (e.g., Shimojo et al., 2001). We varied the occluder-background contrast in order to explore whether the visibility of the occluder would affect the perceived motion direction of the moving objects in the streaming–bouncing stimulus. In daily life, occluder visibility also varies, for example, in day or night time.

2.1. Method

2.1.1. Participants

Seven participants, 2 females and 5 males (including author GR) voluntarily joined the experiment. They were students or researchers of cognitive psychology, 22–40 years of age, with normal or corrected-to-normal vision.

2.1.2. Apparatus

The stimuli were generated and controlled by a personal computer (Sotec PV2240M) and displayed on an 19-in. CRT screen (Mitsubishi RDF 19X; 60 Hz refresh rate; 1024×768 pixels) in a dark room. Each participant viewed the stimuli on the computer screen binocularly from a distance of 57 cm, with a chin-and-forehead rest steadying the participant's head. The center of the computer screen was at eye level.

2.1.3. Stimuli

A subset of the stimuli is shown in Fig. 2. The stimuli consisted of two gray squares (19.7 cd/m^2, 1×1 deg in visual angle), presented on a visual display in which a gray fixation cross (19.7 cd/m^2, 0.84×0.84 deg in visual angle) was set against a dark background (1.38 cd/m^2). The squares appeared 2.51 deg above the fixation cross and were initially separated from each other by 16.67 deg. After a stationary period, the squares moved laterally towards each other with a speed of 10 deg/s, coincided, and continued moving until each square reached the other's starting point. The squares were stationary for 1067 ms and in motion for 1667 ms, so that each stimulus lasted 2734 ms in total.

The moving gray objects moved behind two occluders in the display. There were three variations in the luminance of the occluders. The occluders' luminance could be 65.5 cd/m^2 (high contrast between occluders and background), 19.7 cd/m^2 (intermediate contrast between occluders and background), and 1.49 cd/m^2 (low contrast between occluders and background). In the intermediate contrast condition, the contrast between the occluders and the moving objects was zero. The two occluders were placed around the center of the display at the trajectories of the moving objects. There were seven variations in the edge-to-edge separation between the occluders, which was 0.25, 0.5, 0.75, 1, 1.25, 1.5, or 2 deg. One stimulus was a control condition, in which no fixed objects were placed on the moving objects' trajectories. There were thus 22 stimuli in total: 21 occlusion conditions (three variations in occluder luminance and seven variations in occluder separation) and one control condition.

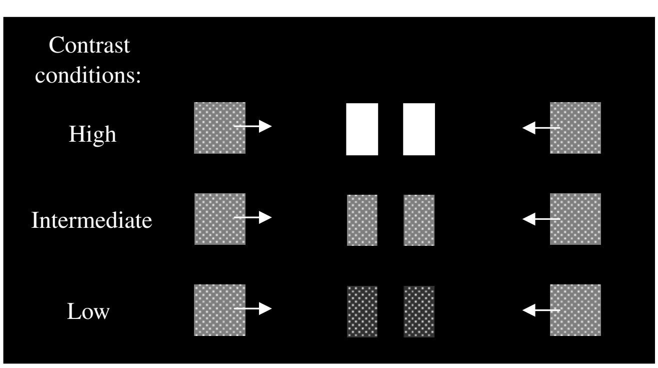

Fig. 2. Sample of the stimuli used in Experiment 1. There were three luminance contrast conditions for the occluders and the background: a high-contrast condition (65.5 versus 1.38 cd/m^2), an intermediate-contrast condition (19.7 versus 1.38 cd/m^2), and a low-contrast condition (1.49 versus 1.38 cd/m^2). (Please note that the figure does not depict the actual luminance contrast conditions used in the experiment.)

2.1.4. Procedure

The participant used a 9-point rating scale to judge whether the movement of the moving squares in the display was a streaming or bouncing movement. Although most experiments with a streaming–bouncing stimulus were done with a 2-alternative forced-choice (2AFC) task (e.g., Sekuler et al., 1997), two participants indicated that in informal viewing conditions they perceived small variations in the strength of the bouncing percepts, referring to a strong bouncing impression as "crisp bouncing" and a weak bouncing impression as "sticky bouncing". We therefore used a 9-point rating scale, with '1' representing a clear streaming impression and a '9' representing a strong bouncing impression. The participants could elect a number in between when their streaming or bouncing impression was less robust. We normalized the obtained data.

The 22 stimuli were judged three times with the rating scale, in a single session of 66 randomized trials. A trial was started by clicking a *start* pane on the computer screen. This was followed by the presentation of the stimulus, followed by the appearance of a screen with buttons marked from 1 to 9. After the participant made his/her judgment by clicking one of the nine buttons, a new trial could be started by clicking the *start* pane again. The experiment started with three warm-up trials, randomly selected from the 66 trials. The participant was allowed to take a break during the experiment, but required to perform three warm-up trials before resuming the experiment.

2.2. Results

Fig. 3 shows the results of Experiment 1. The figure shows that the control condition with no occluders placed on the trajectories of the moving objects yielded dominant streaming. In quite a number of occlusion conditions, however, the bouncing percept was dominant. When the contrast between the occluders and the background was high or intermediate, streaming was dominant only when the spatial separation between the occluders was relatively large (1.5 or 2.0 deg). At smaller separations of 0.5, 0.75 and 1.0 deg, bouncing was dominant. The 0.25 and the 1.25-deg occlusion conditions were ambiguous when the occluder-background contrast was high or intermediate. The low-contrast stimuli yielded somewhat different results than the high- and intermediate-contrast stimuli. Especially at spatial separations of 0.25 and 0.5 deg, the low-contrast stimuli did not induce bouncing as well as the high-contrast and the intermediate-contrast stimuli.

The obtained data were normalized with a square root transformation and subjected to a two-way Analysis of Variance (ANOVA), with spatial separation and contrast condition as independent variables. The main effect of

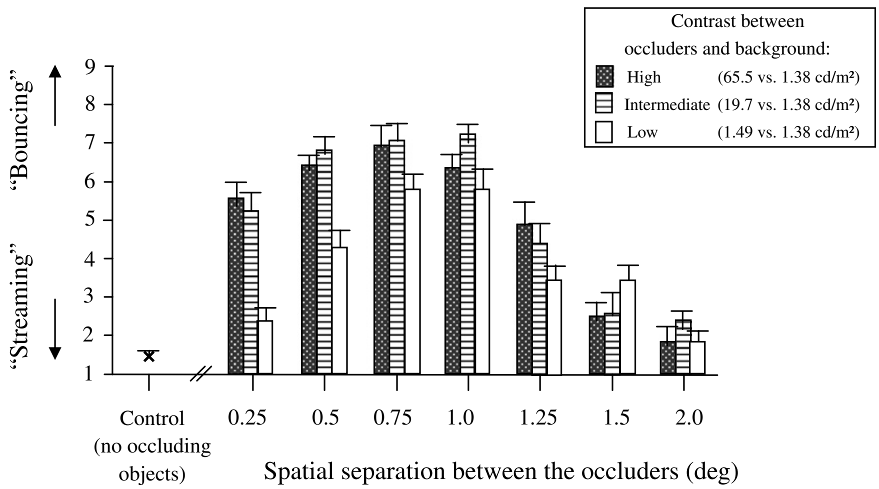

Fig. 3. Results of Experiment 1. The error bars show the standard error of the mean.

spatial separation was significant [$F(6, 240) = 32.98$, $p < .01$]. Post hoc Tukey HSD tests ($p < .05$) showed that in the high-contrast conditions, the 0.5–1 deg stimuli caused significantly better bouncing than the 1.5 and 2 deg stimuli. In the intermediate-contrast conditions, the 0.25–1.25 deg stimuli caused better bouncing than the 1.5 and the 2 deg stimuli. In the low-contrast conditions, the 0.75 and 1 deg stimuli induced significantly more bouncing than the 0.25, 0.5, 1.25, 1.5, and 2 deg stimuli. The ANOVA also showed a significant main effect of contrast condition [$F(2, 240) = 19.31$, $p < .01$] and a significant spatial separation × contrast effect [$F(12, 240) = 4.72$, $p < .01$]. Post hoc Tukey HSD tests ($p < .05$) showed that the high-contrast and intermediate-contrast conditions induced significantly stronger bouncing than the low-contrast conditions when the spatial separation between the occluders was 0.25 and 0.5 deg.

2.3. Discussion

This experiment shows that occluders can induce bouncing in a streaming–bouncing stimulus, but in different degrees depending on occluder-background luminance contrast and the spatial separation between the occluders. The high-contrast conditions induced bouncing when the spatial separation between the occluders was relatively small, so that the occlusion events started in closer spatio-temporal proximity to the meeting point of the moving objects. It is known that external transients such as a sound or a flash induce dominant bouncing when presented in close spatio-temporal proximity to the moving objects' meeting point (e.g., Shimojo et al., 2001). In these cases, the closer the transient is presented to the moving objects' meeting point, the more dominant the bouncing percept becomes. In the present experiment, however, the bouncing percept appeared less dominantly when the occlusion event and the moving objects' meeting point were very close (occluder separation of 0.25 deg). It is also noteworthy that when the occluders were separated by 1.5 and 2 deg, streaming was the dominant percept. Disocclusion in relatively close spatio-temporal proximity to the moving objects' meeting point thus does not seem to induce bouncing. The intermediate-contrast conditions facilitated bouncing under almost the same conditions of occluder separation as the high-contrast conditions, even though the luminance of the occluders and the moving objects was the same. This suggests that local contrast differences between the moving objects and the occluders do not have to be considered as a vital part of an explanation for occluder-induced bouncing.

The low-contrast condition induced bouncing in a less convincing way than the high-contrast and the intermediate-contrast conditions when the spatial separation between the occluders was relatively small. This speaks against a possible explanation of occluder-induced bouncing, which we will call the 'stationary period' explanation from here on. It is known that when the moving objects in a streaming–bouncing stimulus are slowed down or paused deliberately at/near their overlap, bouncing is dominant (Bertenthal, Banton, & Bradbury, 1993; Burns & Zanker, 2000; Sekuler & Sekuler, 1999). Such a change in perceived object speed, or even a pause, could have occurred in the stimuli we have used in the present experiment as well, especially in the conditions in which occluder separation was small. Because the two occluders in these conditions formed an aperture around the moving objects' meeting point, the occluders could have blocked accretion and deletion cues that normally would have signaled contraction and expansion of the objects' overlap. Blocking these cues may have resulted in the perception of a 'stationary period' during the overlap of the moving objects, as schematically depicted in Fig. 4, frames 7–11. The perception of this stationary period in between the two occluders could have resulted in dominant bouncing, in the same way as a physical pause at the objects' overlap does. On the one hand, the results of this experiment support the 'stationary period' explanation of occluder-induced bouncing. The results show that bouncing was induced most strongly

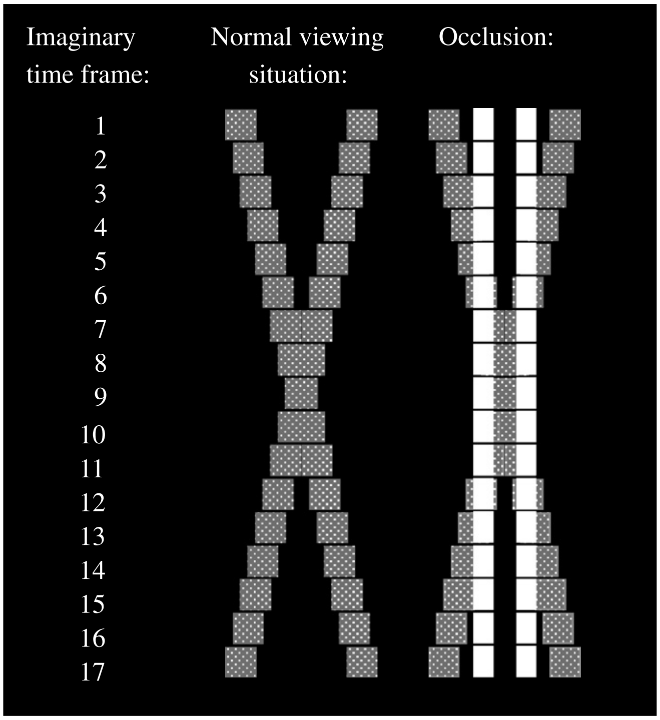

Fig. 4. Schematic impression of how occluders may cause the perception of a stationary period in the streaming–bouncing stimulus. In frames 7–11 in the occlusion condition, the occluders block the contracting and expanding motion (accretion and deletion cues) of the overlapping objects from view.

when the spatial separation between the occluders was equal (1 deg) or smaller than the width of the moving objects. As compared to the other conditions, deletion and accretion cues were occluded most effectively here. On the other hand, the 'stationary period' explanation cannot account fully for why bouncing is more dominant in some contrast conditions than in others. In all the contrast conditions, the same contraction and expansion cues were (un-)available during the overlap of the moving objects. The low-contrast conditions should therefore have yielded the same 'stationary period' as the high-contrast and the intermediate-contrast conditions. Yet the low-contrast conditions produced significantly less bouncing percepts than the high- and intermediate-contrast conditions, under spatial separations of 0.25 and 0.5 deg between the occluders. Furthermore, also when the spatial separation between the occluders was wider (1.25 deg) than the width of the moving objects (1 deg), bouncing was induced to some extent.

The finding that bouncing was less dominant in the low-contrast conditions seems to suggest that the visible presence of the occluders facilitates the bouncing percept better than the (possible) perception of a stationary period at the moving objects' overlap. The occluder-background contrast in the low-contrast condition was 8% (1.49 cd/m^2 versus 1.38 cd/m^2), and it is known that viewers' performance on an object recognition task with focal vision becomes worse when the object-background contrast is 10% or less (Avidan et al., 2002). Since viewers in the present task mainly saw the occluders with peripheral vision, it is possible that they could not easily discern the occluders from the background. Several studies on amodal completion in static scenes have shown that the visibility of occlusion cues affects the perceptual completion of an object (e.g., Kellman & Shipley, 1991; Rensink & Enns, 1998). Especially the visibility of edges (T- and L-junctions) that indicate the overlap of the occluded object by the occluding object is important for perceptual completion. Murray, Sekuler, and Bennet (2001) used zero-contrast occluders, i.e., occluders with the same luminance as the background, and found that without occlusion cues such as T- and L-junctions, amodal completion was impaired. In Experiment 2, we investigated whether or not such 'virtual' occluders induced the same degree of bouncing as the luminance-defined occluders.

3. Experiment 2

The results of Experiment 1 suggest that the visibility of occlusion cues affects the perception of motion direction of occluded objects in a streaming–bouncing stimulus. In this experiment, we tested three different occlusion conditions (Fig. 5). Apart from the luminance-defined, high-contrast conditions we used in Experiment 1, we generated 'virtual occlusion' (zero-contrast) and 'brief occlusion' conditions. The virtual occluders were used to investigate whether the presence of occlusion cues is necessary to induce bouncing. The virtual occluders in this experiment had the same luminance as the background and were therefore invisible, yet functionally present. It is known that static completion tasks yield different results when virtual occluders are used instead of luminance-defined occluders (Murray et al., 2001; Rensink & Enns, 1998). A factor that may have contributed to this is that in these static completion tasks stimuli were used in which aligning fragments of a figure were visible at more than one side of an occluder, as for example in a stimulus in which a bar is occluded in the middle.

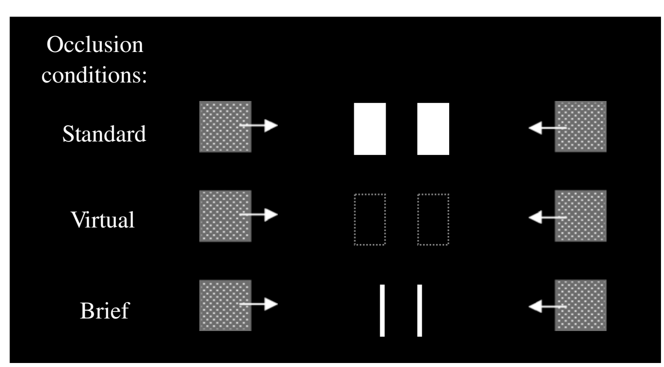

Fig. 5. Sample of the stimuli used in Experiment 2. There were three occlusion conditions. One condition contained visible occluders with a size of 1×0.67 deg ('real occlusion'). A second ('virtual occlusion') condition contained occluders that were functionally present but invisible because they had the same luminance as the background (schematically indicated by the dotted gray edges). A third condition consisted of visible occluders with a size of 1×0.125 deg ('brief occlusion').

Under real occlusion, the visible object fragments are amodally completed into a single object (e.g., a single bar). Under virtual occlusion, however, the lack of occlusion cues may have caused the objects fragments to be regarded as a collection of separate objects themselves (e.g., two separate bars). Little is known, however, about similar performance differences in dynamic completion tasks under luminance-defined and virtual occlusion. Scholl and Pylyshyn (1999) and Horowitz et al. (2006) used virtual occlusion conditions in a task in which multiple objects had to be tracked, and they found that virtual occlusion conditions yielded the same results as 'real' occlusion conditions. Sekuler and Sekuler (1999) also did not find a performance difference between real and virtual occluders in their streaming–bouncing study with a single occluder. The authors in these studies stated that the lack of a performance difference happened because the virtual occluders could still be regarded as opaque, occluding surfaces, in spite of their invisibility. However, in view of the fact that occlusion cues are considered as necessary to trigger completion of an occluded object in static scenes (e.g., Kellman & Shipley, 1991) and the low-contrast results of Experiment 1 in the present study, it is possible that in our paradigm it makes a difference whether occlusion cues are present or not. If the visible presence of occlusion clues affects the amount of bouncing responses, then the virtual and the real occlusion conditions should yield different results. This would imply that occlusion and completion per se influence perceived motion direction in our paradigm.

We also used 'brief' occlusion conditions in this experiment in order to test whether the size of the occluders (i.e., the duration of the occlusion event) affects the perception of the motion direction in the streaming–bouncing stimulus. The brief occlusion conditions employed very thin occluders, one-eighth of the size of the moving objects. In the case of static object completion, it is known that the time in which the object is completed depends on the amount of occlusion of the object. Small amounts of occlusion are dealt with quickly by the visual system and are less time-consuming than the completion of objects that are heavily occluded (Guttman, Sekuler, & Kellman, 2001; Shore & Enns, 1997). Under the assumption that bouncing is perceived when constant motion processing of the moving objects is interrupted, we tested whether brief interruptions would less strongly facilitate the bouncing percept.

3.1. Method

Six participants joined the experiment. Three of them had participated in Experiment 1. The two participants who saw slight variations in the bouncing percepts did not participate in this experiment, because we used a 2AFC-task in order to get a fair amount of judgments (12 in total) for each stimulus. The task of the participant was to judge whether he/she perceived each stimulus as streaming or bouncing. The stimulus parameters were the same as in Experiment 1, except for the following points. There were 13 stimuli, one of which was a control stimulus without occluding objects. The remaining 12 stimuli comprised three basic occlusion conditions (Fig. 5) with four variations in spatial separation between the occluders: 0.5, 1, 1.5, and 2 deg. In all three occlusion conditions, the luminance of the background was 1.38 cd/m^2 and that of the moving objects was 19.7 cd/m^2. The first occlusion condition was a high-contrast condition, in which the size of the occluders was 1×0.67 deg and their luminance was 65.5 cd/m^2. This 'real occlusion' condition was the same as that in Experiment 1. The second occlusion condition was a 'virtual occlusion' condition, in which the size of the occluders was 1×0.67 deg and the luminance of the occluders was the same as that of the background. The occluders thus were functionally present, yet invisible. The third occlusion condition was a 'brief occlusion' condition consisting of thin occluders. The size of the occluders was 1×0.125 deg and their luminance was 65.5 cd/m^2. The 13 stimuli were judged 12 times by each participant, in three sessions of 52 randomized stimuli.

3.2. Results

Fig. 6 (left panel) shows the overall results of Experiment 2. Interestingly, two of the six participants obtained relatively high bouncing scores for the control condition (Fig. 6, right panel). These two participants had not participated in Experiment 1, so we do not think that the use of the 2AFC-task instead of a rating scale caused these high bouncing scores. Whereas the other four participants generally judged the control condition as predominantly streaming (Fig. 6, middle panel), the two participants saw the control condition in a truly bistable way—that is, they obtained about equal amounts of streaming and bouncing scores. Moreover, they judged the virtual occlusion conditions and the brief occlusion conditions differently than the other four participants. The middle panel of Fig. 6 shows that the four participants with dominant streaming in the control condition judged the brief occlusion conditions mainly as streaming. They saw bouncing more frequently in the virtual occlusion conditions, yet—by far—not as much as in the real occlusion conditions when the spatial separation between the occluders was 0.5 or 1 deg. The right panel in Fig. 6 shows that the two participants who saw bouncing in about half of the control trials judged the brief occlusion conditions at about the same level as the control condition. They showed the same bounce-inducing effect of the real occluders as the other four participants (especially in the 0.5 and 1-deg conditions), yet they also showed a remarkable release from this effect in the virtual occlusion conditions. The virtual occlusion conditions for these two participants were predominantly streaming, and thus rendered *fewer* bouncing percepts than the control condition.

Because of the diverse nature of the data, we subjected the data for all the stimuli to the non-parametric Friedman

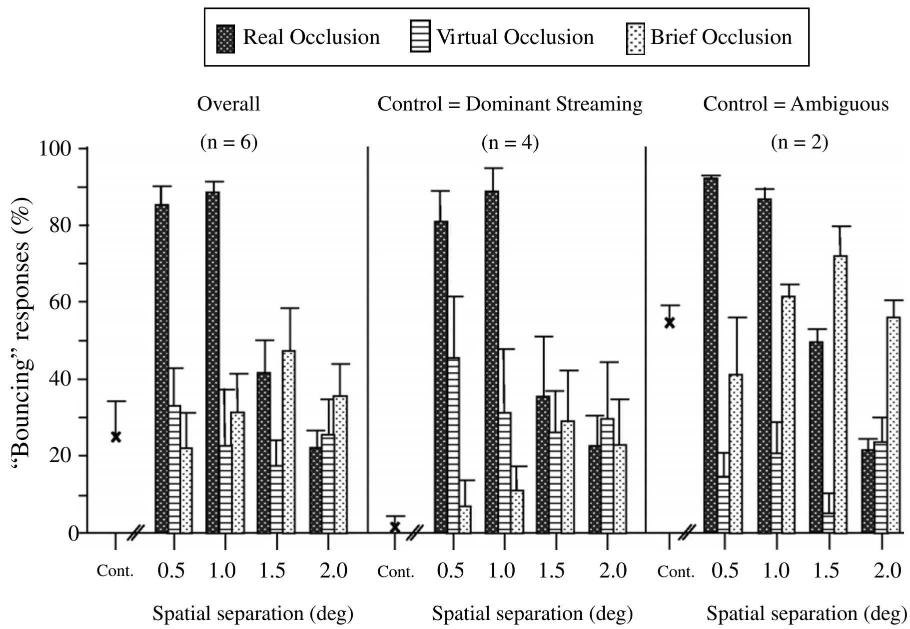

Fig. 6. Results of Experiment 2. The data of all six participants are depicted in the left panel. The data of four of the six participants are depicted in the middle panel. This group perceived the control condition without occluders generally as streaming. The data of the other two participants are depicted in the right panel. These participants scored almost equal numbers of streaming and bouncing judgments in the control condition. The error bars show the standard error of the mean.

test. The test was significant ($Fr = 29.73$, $p < .01$, at $n = 6$ and $df = k - 1 = 12$). Post hoc tests ($p < .05$) showed significantly more bouncing scores for the real occlusion conditions with 0.5 and 1 deg of spatial separation as compared with the real occlusion conditions with 1.5 and 2 deg of separation between the occluders. The real occlusion conditions with 0.5 and 1 deg of separation yielded significantly more bouncing than the virtual occlusion conditions and the brief occlusion conditions with the same spatial separations.

3.3. Discussion

The real occlusion conditions in this experiment produced a bounce-inducing effect similar to that found in Experiment 1. Bouncing occurred in the conditions with the smaller (0.5 and 1 deg) spatial separation between the occluders. When the separation grew larger, however, streaming became dominant. This experiment also shows that when clear occlusion cues were not present, as in the virtual occlusion conditions, a release from the bounce-inducing effect occurred. The virtual occlusion conditions yielded rather dominant streaming for all six participants.

The significant differences between the real and the virtual occlusion conditions show that the 'stationary period' explanation cannot account for the bounce-inducing effect of occlusion by itself. We have already seen in Experiment 1 that in conditions that should have yielded similar stationary periods, differences in the perception of streaming or bouncing occurred. Although the functional occlusion of the moving objects occurred in a similar way in Experiment 1, the high-contrast conditions facilitated bouncing better than the low-contrast conditions. Also in the present experiment, the real and the virtual occluders functionally occluded the moving objects in a similar way. Possible stationary periods due to the occlusion of the contracting and expanding motion of the moving objects at their overlap should have been equal in both conditions. However, the real occluders significantly induced bouncing better than the virtual occluders in some conditions.

The differences between the real and the virtual occlusion conditions indicate that the visible presence of occlusion cues is important for occluder-induced bouncing to occur. This implicates that processes of occlusion and perceptual completion per se modulate occluder-induced bouncing. The finding that the thin occluder (0.25 deg) in this experiment did not induce bouncing seems to be in line with this. In the case of static object completion, it is known that the speed of object completion depends on the amount of object occlusion (Guttman et al., 2001; Shore & Enns, 1997). In a static scene, a factor that can contribute to this is the speed with which object fragments that are not occluded are grouped. Such grouping may also have speeded up the perceptual completion in the present paradigm. In the case of brief occlusion, the leading portion of the moving object reappeared from behind the occluder while its trailing portion still had not moved under occlusion yet. The visual system thus could have grouped the leading and the trailing portion of the object, with swift completion as a result. Such swift completion would have interfered less with constant motion processing, with dominant streaming as a result. In Experiment

3, we tried to replicate the effects of occluder visibility and occlusion duration on the perceived motion direction in the streaming–bouncing stimulus.

4. Experiment 3

In this experiment, we used 'real' and 'virtual' occlusion conditions, as well as control conditions without occluders, under various object speeds in the streaming–bouncing display. The different occlusion conditions were employed to see whether the results of Experiment 2 could be replicated. In other words, we wanted to test whether the perception of occlusion cues is indeed necessary to facilitate the bouncing percept. Object speed was varied to further explore the influence of occlusion duration on the perceived motion direction of the moving objects in the streaming–bouncing stimulus. We used the same object speed as in Experiments 1 and 2, along with a slower and a faster object speed. We hypothesized that streaming would become the dominant percept even under luminance-defined olcuders, when the object speed is high and, hence, the occlusion events are brief.

4.1. Method

Six participants joined the experiment. Three of them had participated in Experiments 1 and 2. The stimulus parameters were the same as in Experiment 2, except for the following points. There were nine stimuli, consisting of combinations of three different object speeds and three different occlusion conditions. The speed of the moving objects was 5, 10 or 40 deg/s, made by changing the step-size of the objects. The objects moved either in a display with real (visible) occluders, with virtual (invisible) occluders, or without occluders. The width of the occluders in the real and virtual occlusion conditions was 1×0.75 deg and the spatial separation between the occluders was 0.5 deg. Each stimulus was judged three times on the rating scale, in a single session consisting of 27 randomized trials.

4.2. Results

The results of Experiment 3 are shown in Fig. 7. The results show that streaming was the dominant percept when object speed was very high (40 deg/s). At slower object speeds (5 and 10 deg/s), bouncing was dominant in the real occlusion condition, but not in the virtual occlusion and the control conditions. The data were normalized by a square root transformation and subjected to a two-way ANOVA. The two main effects of stimulus type [$F(2,68) = 40.13$, $p < .01$] and object speed [$F(2,68) = 81.10$, $p < .01$] were significant, as well as the interaction effect [$F(4,68) = 21.68$, $p < .01$]. Post hoc Tukey HSD comparisons ($p < .05$) showed that the real occlusion condition induced the bouncing percept significantly better than the virtual occlusion and the control condition when the object speed was 5 or 10 deg/s. When the object speed was

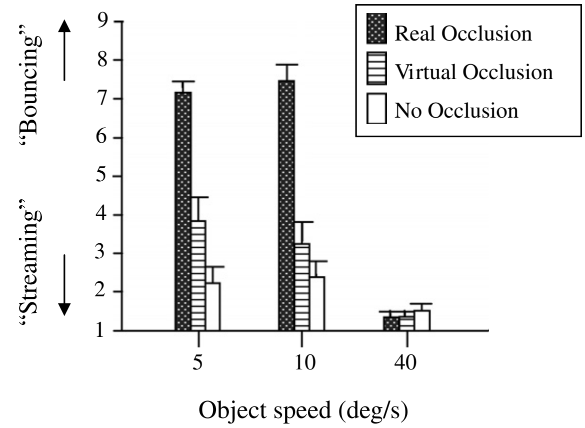

Fig. 7. Results of Experiment 3. The error bars show the standard error of the mean.

5 deg/s, the virtual occlusion condition induced significantly stronger bounching than the control condition. In the real and virtual occlusion conditions, an object speed of 40 deg/s resulted in significantly less bouncing than an object speed of 5 or 10 deg/s.

4.3. Discussion

The results of Experiment 3 replicate those of Experiment 2 in that occlusion cues were necessary to induce bouncing. Virtual occlusion caused better bouncing than the control condition when the object speed was 5 deg/s. In both speed conditions of 5 and 10 deg/s, however, real occlusion induced significantly better bouncing than virtual occlusion. The results further show that brief occlusion events, such as those in the high object speed conditions of 40 deg/s, hardly produced any bouncing at all—not even in the real occlusion condition. At this object speed, the occlusion event started 33.33 ms (two frames) before the moving objects' meeting point and the occlusion event was 16.67 ms (one frame). This indicates that in order to induce bouncing, real occlusion cues not only have to be clearly visible, but they also have to be visible for a certain amount of time before the moving objects' meeting point.

5. General discussion

The results of three experiments showed that occlusion events can alter the perceived motion direction of the two objects in the ambiguous streaming–bouncing stimulus. In this stimulus, two identical objects that move through each other can either be seen as streaming through each other, as they physically do, or as bouncing off each other at the objects' meeting point. Experiments 1 and 2 showed that the bouncing percept was dominant when the two objects moved under occlusion in rather close temporal proximity to the objects' meeting point. In these experiments, occluder-induced bouncing was most profound when occlusion started about 100 ms before the moving objects' meeting point. Experiment 3, however, showed that bouncing could also be induced when occlusion started 200 ms before the moving objects' meeting point.

The experiments showed that the bouncing percept was most profound when the two objects moved under clearly visible, luminance-defined occluders. Streaming was the dominant percept when the occluders had a low or a zero-contrast in relation to the background. Experiments 2 and 3 showed that dominant bouncing was not induced when occlusion events were very short (one frame), even when the occlusion started in close temporal proximity to the moving objects' meeting point and the occluders were clearly visible.

One possible explanation for the bounce-inducing effect of occlusion, the 'stationary period' explanation, states that bouncing is perceived because the occluders block the accretion and deletion cues of the moving objects at the objects' meeting point. Without these cues, the observers might perceive a pause in the motion of the two objects at their overlap, in spite of the fact that the objects are physically moving. The perception of a pause in the object motion can induce the bouncing percept, as is the case when the objects are physically slowed down or paused at their meeting point (e.g., Bertenthal et al., 1993). This 'stationary period' explanation can account for a number of findings, such as the finding that bouncing was dominant especially when the spatial separation between the occluders was equal to or smaller than the width of the moving objects when they overlapped (Experiment 1). The explanation can also account for the finding that thin (brief) occluders did not induce dominant bouncing. Thin occluders cannot block the accretion and deletion cues very effectively at the overlap of the moving objects (Experiment 2). Finally, the finding that bouncing was also not dominant a fast object speed (Experiment 3) can be accounted for by the explanation, because increasing the object speed would result in increasingly shorter 'stationary periods' between the occluders. However, the 'stationary period' explanation cannot account for one important finding: the significant difference between the bounce-inducing effects of luminance-defined occluders and 'virtual', invisible occluders (Experiments 2 and 3). In both these occlusion conditions, the accretion and deletion cues at the overlap of the moving objects were blocked from view in the same way, so that identical 'pause' images should have appeared on the observers' retinas. Virtual occlusion, however, did not induce bouncing very strongly.

Although we cannot completely rule out any contribution of the perception of a stationary period in our paradigm, an alternative, tentative explanation for occluder-induced bouncing is that objects completion, and the maintenance of an abstract representation of the objects behind the occluders, could have temporarily interfered with constant motion processing of the same object. The explanation follows the idea behind the bounce-inducing effects of the presentation of a brief sound or flash in close spatio-temporal proximity to the moving objects' meeting point (Shimojo et al., 2001; Watanabe & Shimojo, 1998). These authors suggested that when attentional resources are engaged in the interpretation of the transient sound or flash, such resources are not available to track the moving objects as moving through each other at the objects' meeting point, with dominant bouncing as the result. In a similar vein, bouncing could have occurred in certain occlusion conditions because attentional resources were too heavily engaged in object completion and maintaining a representation of the two objects when they were about to meet. A number of studies suggest that maintaining a representation of an object under occlusion requires attention (for a review: Hollingworth, Williams, & Henderson, 2001; Rensink, 2000).

This 'completion' explanation can account for the finding that bouncing was most prominent when occlusion started in close (spatio-)temporal proximity to the moving objects' meeting point in the following way. When the spatial separation between the occluders became larger, completion of the moving objects could have been finished before the moving objects met. Attentional resources then would be available for constant motion processing (streaming). The 'completion' explanation can also account for the finding that bouncing was not prominent when occlusion was brief. In the case of brief occlusion, possibly fewer attentional resources were required for only a short amount of time. Also in this case, attentional resources would be available for tracking the moving objects as moving through each other. The 'completion' explanation thus assumes that perceptual completion of an object, once initiated, takes a minimum amount of time. In Experiment 1, bouncing was most prominent in conditions in which occlusion started within a range of about 100 ms before the objects' meeting point (separation conditions of 0.25–1 deg). Experiment 3, however, showed that occlusion could also be prominent when occlusion started 200 ms before the moving objects' meeting point. Although more research is necessary to study these temporal characteristics of dynamic perceptual completion, it is interesting to note that studies on static perceptual completion reported that completion requires a minimum amount of 75 ms (Murray et al., 2001) or between 75 and 200 ms (Sekuler & Palmer, 1992).

The difference between the 'stationary period' explanation and the 'completion' explanation is that the latter might cope with the finding that real occluders-induced bouncing better than virtual occluders (Experiments 2 and 3). At first glance, though, this finding cannot be explained in terms of the idea that bouncing occurs when attentional resources are drawn away from tracking of the moving objects. Such resources must have been allocated to the interpretation of the virtual occluders as well, because of their abrupt appearance on the screen and the uncertainty about their size. However, although potentially no different from a transient sound or flash, the virtual occluders did not induce bouncing. What might have happened is that the virtual occluders were not efficient as a percept switch simply because they did not fully trigger perceptual completion of the moving objects. Studies related to the completion of stationary objects under occlusion have shown that occlusion cues such as edges (L- and T-junctions) at the intersections of the occluding and the occluded object are necessary to trigger completion (e.g., Kellman & Shipley, 1991). So-called border-ownership coding of these edges occurs mainly in area V2 and the cortical processing that leads to border-ownership discrimination requires 25 ms or less in awake behaving monkeys (Zhou, Friedman, & von der Heydt, 2000). The process is said to occur independent from attention (von der Heydt, Sugihara, & Qiu, 2004), and may have taken place in all the stimuli we have used here, be it occlusion, non-occlusion, or virtual occlusion ones. Rensink and Enns (1998) argued that processes of amodal completion start with the assignment of borders to the occluding object rather than to the occluded object (see also Rubin, 2001). In the virtual occlusion conditions, however, the border between the moving and the fixed objects may often have been assigned to the moving objects instead, so that these looked as though they were disappearing. With attentional resources not allocated to perceptual completion, streaming could therefore become dominant in the virtual occlusion conditions.

Recent research, in which tracking of multiple objects under various types of occlusion was investigated (Alvarez, Horowitz, Arsenio, Dimase, & Wolfe, 2005; Horowitz, Brinkrant, Fencsik, Tran, & Wolfe, 2006), has suggested that attentional resources are allocated differently depending on whether the tracked objects move under real occlusion, or whether the tracked objects suddenly go out of sight for a period of time. Horowitz et al. (2006) found that in the period that the tracked objects vanished, more attentional resources were available for a dual task than when the tracked objects were occluded. The authors argued that when the objects vanished simultaneously, their position and (possibly) direction information were quickly stored so that attention could have been used for another task. The authors argued that occlusion cues, however, would discourage this process of storage and attention release, by indicating that the tracked objects are still present under occlusion and the focus of attention. This idea would be compatible with our findings, if it were not for the fact that Horowitz and colleagues only used virtual occluders in their study and, similar to Scholl and Pylyshyn (1999), assumed that these would function in a similar way as real occluders. There are obvious differences in the paradigms between theirs and our study, but it is possible that the results display a similar process. In future research it is necessary to test the validity of the 'completion' explanation we have proposed here by investigating whether there is a difference in the availability of attentional resources during real and virtual occlusion in a dual-task paradigm or in a multiple-object tracking task as used by Horowitz et al. (2006).

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